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Seismic Risk Assessment of Asymmetric Buildings using Fragility Curves

Upasana R. Rana [1, *], Snehal V. Mevada [2] and Vishal B. Patel [3]

[1] Structural Engineering Department, PG Research Scholar, Birla Vishvakarma Mahavidyalaya, Vallabh Vidyanagar, 388 120, India
[2,3] Structural Engineering Department, Assistant Professor, Birla Vishvakarma Mahavidyalaya, Vallabh Vidyanagar, 388 120, India

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Abstract

It is very important and necessary to assess the seismic risk for the buildings subjected to uncertain and highly unpredictable dynamic forces produced from earthquakes. Fragility curves are the best tools for the representation of seismic risk assessment. In the present study, risk assessment of structure subjected to seismic loading is evaluated. Further, the effects of different eccentricities are also studied for seismic risk assessment. The fragility curves are developed for G+5 storied RCC bare frame building as well as G+5 storied RCC building with shear wall. The considered buildings are subjected to ground motions of past recorded earthquakes. Buildings with different eccentricities and various structural configurations are studied for various failure criteria. The responses of the considered buildings subjected to earthquake excitations are evaluated by Incremental Dynamic Analyses. Fragility curves are developed using Monte Carlo method considering various performance levels as per ATC-40. It is observed that for immediate occupancy failure criteria, the probability of failure is increased constantly with increasing the percentage of structural eccentricity. Further, it is observed that very less variation is observed in the probability of failure under life safety and collapse prevention failure stages.

Key Words: Risk Assessment, Fragility Curves, Seismic load, Incremental Dynamic Analysis

1. Introduction

Risk Assessment of structures implies estimation of the limit state probabilities to evaluate the performance and determine the overall capacity of structure under seismic loading. The behavior of structures subjected to uncertain parameters is highly unpredictable. Risk assessment is useful to determine the behavior of structures subjected to uncertain parameters. There are three types of uncertainties present in the structure; a) random ground excitation; b) statistical uncertainty; and c) model uncertainty [2]. The most uncertain parameter which causes the maximum damage to the structure is random ground excitation called an earthquake.

The structure is always vulnerable to the earthquake, so risk assessment of structure subjected seismic loading will become important to study. Accuracy of the reliability analysis depends upon how accurately all the uncertainties account in the analysis. The most important aspect of the reliability analysis is the consideration of uncertainties that make structures vulnerable to failure for a predefined limit state. Risk assessment is extension of reliability analysis by considering the consequences of failure [1]. Application of risk assessment is to determine the capacity of the structure, damage states estimation, loss estimation, retrofitting and requirement of strengthening [3].

In the past, many researchers have investigated seismic vulnerability, risk assessment, probabilistic seismic demand analysis (PSDA), multi-hazard risk associated with collapse limit state and develop the fragility curves by regression analysis or simulation-based methods. Celik and Ellingwood [4] studied on seismic vulnerability & risk assessment by simulation-based reliability analysis and determine seismic fragility curves and damage states. Mojiri et. al. [5] studied on seismic probability risk assessment & probabilistic seismic demand analysis (PSDA), RC models using excitation generated by experimental shake tables and determine seismic demand levels and fragility curves. Arabzadeh and Galal [6] studied on sensitivity & effect of Fiber Reinforced Polymer (FRP) retrofitting on the seismic collapse of the system for different tensional effects and found the effective strengthening layout by FRP and develop fragility curves. Faghihmaleki et.al. [7] studied on a probabilistic framework for multi-hazard risk associated with collapse limit state of G+8 RC moment frame with shear wall using software Seismostruct under the blast and seismic loading condition and develop fragility curves. Huang et.al. [8] studied on probability density evaluation method (PDEM) of analysis, which is a method of dynamic reliability & seismic fragility analysis for development of fragility curves.

Fragility analysis is the analysis to determine the behavior of structure with the constant increase in Peak Ground Acceleration. It is aimed to determine fragility curves. The fragility curve is half a bell shape curve with normal probabilistic distribution of damage state. Fragility curves are the best representation of risk assessment. Fragility curve shows the continuous relationship between ground motion intensity measure and probability of exceeding predefine

*Corresponding author. Tel: +919737621031; E-mail address: upasanarana9597@gmail.com

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damage state for specified structure. Peck ground acceleration (PGA), peck ground velocity or spectral acceleration considered as a ground motion Intensity Measure (IM) and base shear, storied drift or lateral displacement can be considered as predefine Damage State (DS) [3].

It is very obvious that symmetric structure is not possible each time because of variation in site of structure, architectural demand and structural demand as well. Therefore, asymmetricity of the structure cannot be avoided and to study the effect of eccentricity in seismic risk assessment will become important. The variation in capacity and performance of structure with varying eccentricity can studied by application of risk assessment & determine fragility curve.

The main objective of this study is to evaluate the seismic risk of reinforced concrete structure by determining the fragility curve. Further, the effects of various eccentricities on seismic risk assessment of structure are also studied.

2. Fragility Analysis

2.1 Monte Carlo method

Fragility analysis can be done by analytical methods or by simulation method. From previous researches it is proved that the Monte Carlo method of simulation is the most effective method of simulation. The Monte Carlo method is based on the integration of a given problem by mean value interpretation using stochastic experiment which gives a central estimation of the value of integral [2]. Monte Carlo method is a technique that involves using random numbers and probability to solve the problems. It calculates a set of random values of the probability functions. Depending upon number of uncertainties and the ranges specified for them, a Monte Carlo simulation performed until convergence of both input & output variables to their mean is reached & value of standard deviation becomes stable [1]. Monte Carlo simulation produces a distribution of possible outcome values.

The probability of failure P_f is obtained as [1]

$$P_f = \iint \dots \int_{g(x)\leq 0} Fx(X) \quad dx \tag{1}$$

in which $Fx(X)$ is the joint density function of variables $x_1; x_2; \dots x_n$ and dx stands for $dx_1; dx_2; dx_3;\dots\dots; dx_n$ [1].

This Monte Carlo simulation of basic variables according to their probabilistic characteristics and then feeding them in the limit state function, the equation of probability of failure for function g (X) < 0 will become [1]:

$$P_f = N_f / N \tag{2}$$

in which N = total number of simulation cycles and

N_f = number of failed cycles

For accuracy of the estimated probability of failure, it is better to approximately compute the variance of the estimated probability of failure, which is done by assuming each simulation cycle to constitute a Bernoulli trial [1]. Therefore, N_f in N trials can be considered to follow a binomial distribution. The variance of the estimated probability of failure can be computed approximately as [1]:

$$var\ (P_f) = (1 - P_f)\ (P_f) / N \tag{3}$$

The statistical accuracy of the estimated P_f is measured by the coefficient of variation given by:

$$cov\ (Pf)\ \cong\ \frac{\left[\frac{\sqrt{((1-Pf)(Pf))}}{\sqrt{N}}\right]}{Pf} \tag{4}$$

The smaller the coefficient of variation, the better the accuracy is. Accordingly, N is decided.

2.2 Method for Determining Fragility Curve

The first step to determine fragility curve is modeling of structure. Modeling is done by various available software tools like Seismostruct or OpenSEES. RC frame or steel structure with a load transfer mechanism needs to define, which requires number of stories and bays, grade of concrete and yield strength of steel, reinforcement details of beams and columns and all other data which are necessary to define the model. Next step is to define of uncertainties which are classified as randomness and variability of ground excitation in terms of earthquake records (time histories); statistical uncertainty in terms of material uncertainties like modulus of elasticity of concrete (E_c), yield strength of steel (f_y) and compressive strength of concrete (f_{ck}) and model uncertainty, which arises due to imperfection of mathematical modeling which are considered.

After defining the uncertainty, it is necessary to determine failure criteria and performance limit. The threshold values derived from the performance limit of ATC 40 chord rotations and capacity curve of each model using nonlinear methods of analysis. These values are used as boundary value of Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) levels for the development of fragility curves.

Incremental Dynamic Analysis is carried out, collect the results in terms of uncertain parameters vs failure criteria which called Response Clouds. Application of Monte Carlo method on results of Incremental Dynamic Analysis gives fragility curves.

3. Numerical Study

3.1 Details of Building

In the present research work, a G+G+5 storied RCC frame building and G+G+5 storied RCC building with shear wall are considered for development of fragility curve. ETABS software tool used to check the safety and stability of structure. The Isometric view and plan of G+5 storied RCC frame building and G+5 storied RCC building with shear wall are shown in figures 1 and 4.

3.3 Consideration of Asymmetricity

For G+5 storied RCC Frame building, four models are considered with eccentricity ranges between 0 to 5%, 5 to 10%, 10 to 15% and 15 to 20% which are 0%, 7.50%, 13.25% and 17.70%. The eccentricity developed by shifting the center

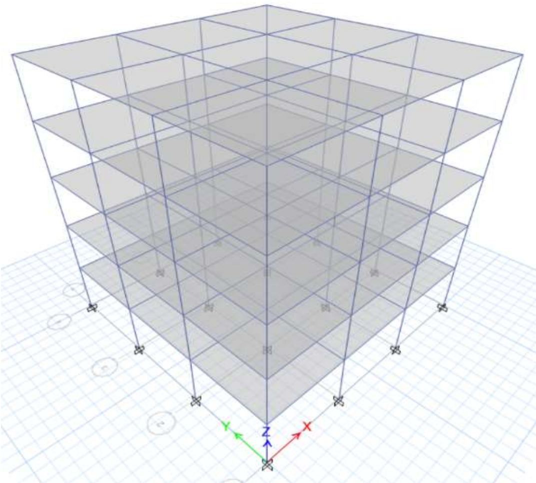

Fig. 1 Isometric view of G+5 storied RCC Frame Building

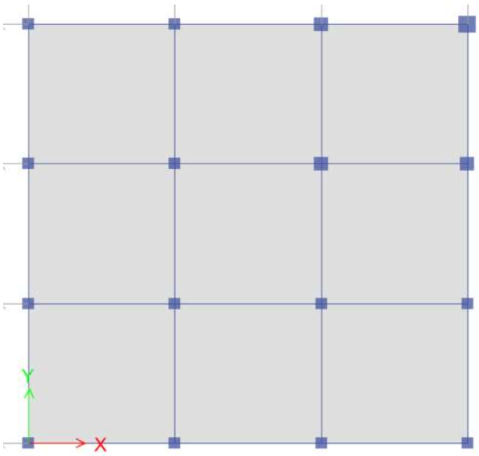

Fig. 2 Plan of G+5 storied RCC Frame Building

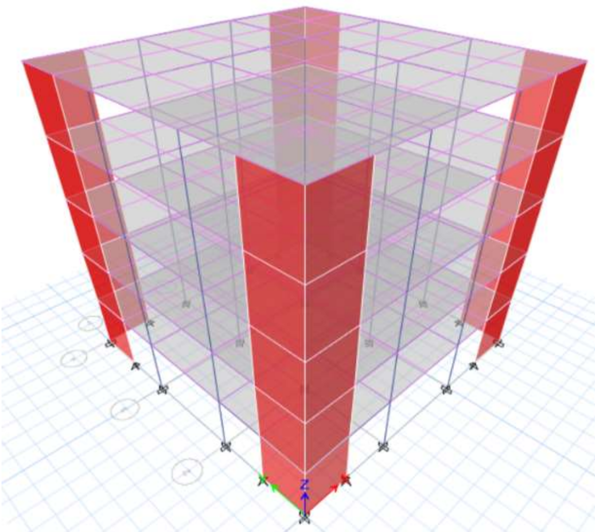

Fig. 3 Isometric view of G+5 storied RCC Building with Shear Wall

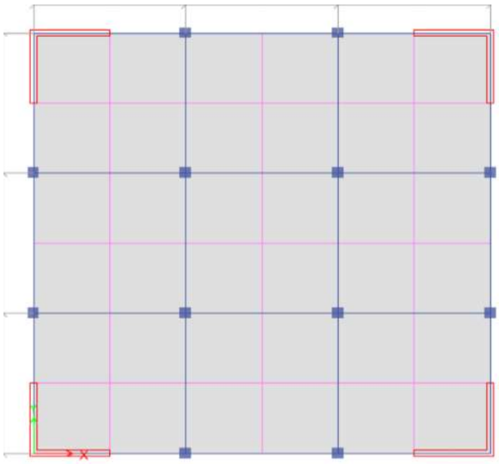

Fig. 4 Plan of G+5 storied RCC Building with Shear Wall

Table 1 Properties of Building

Parameter	Value
Concrete Grade	M25
Steel Grade	Fe415
Storey Height	3.5m
Total Height of Building	17.5m
C/C Bay Distance	5m
Beam Size	230mm x 460mm
Column Size	400mm x 400mm
Slab Thickness	120mm
Wall Thickness	230mm
Seismic Zone	5
Importance Factor (I)	1
Response Reduction Factor (R)	5
Soil Type	Hard
Live Load	2 kN/m^2

Table 2 Time Histories used in IDA

Earthquake	PGA (m/sec^2)
Imperial Valley, 1940	0.312
Loma Prieta, 1989	0.966
North Ridge, 1994	0.897
Kobe, 1995	0.821

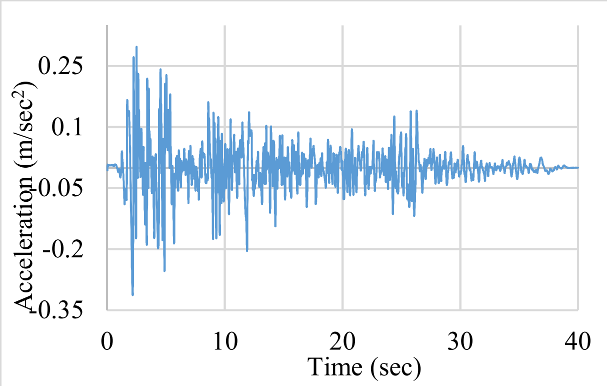

Figure 5 Time History of Imperial Valley, 1940

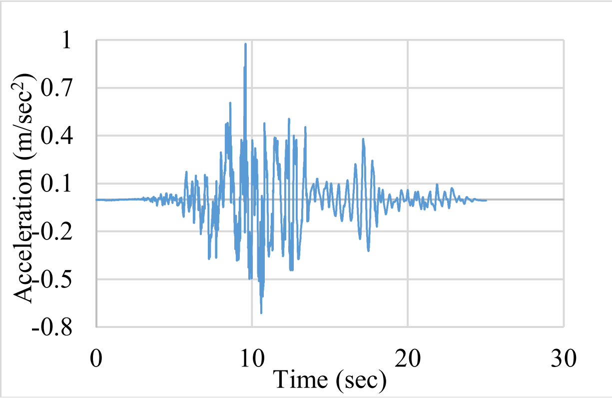

Figure 6 Time History for Loma Prieta, 1989

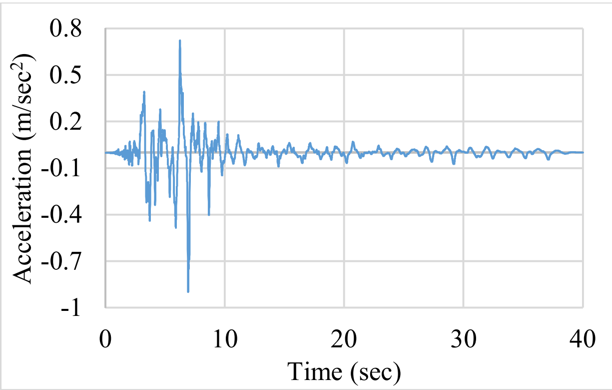

Figure 7 Time History for North Ridge, 1994

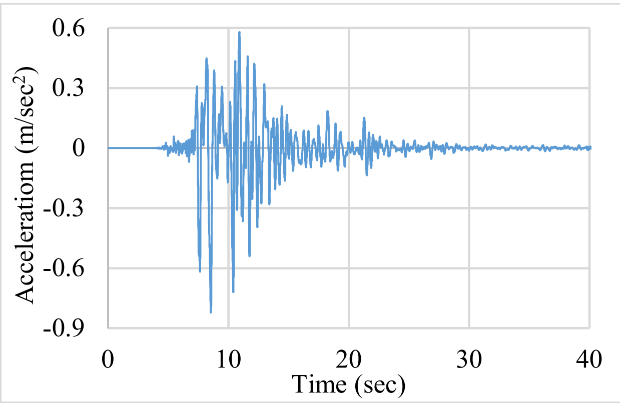

Figure 8 Time History of Kobe, 1995

and 17.70%. The eccentricity developed by shifting the center of stiffness which is done by varying column dimensions as shown in figure 9. The dimension of three columns which are indicated as '1' and one corner column, which is indicated as

Table 3 Dimensions of corner Columns for various eccentricity cases

Model	Eccentricity	Column '1'	Column '2'
1	0%	400 mm X 400 mm	400 mm X 400 mm
2	7.5%	450 mm X 450 mm	525 mm X 525 mm
3	13.25%	500 mm X 500 mm	600 mm X 600 mm
4	17.70%	600 mm X 600 mm	625 mm X 625 mm

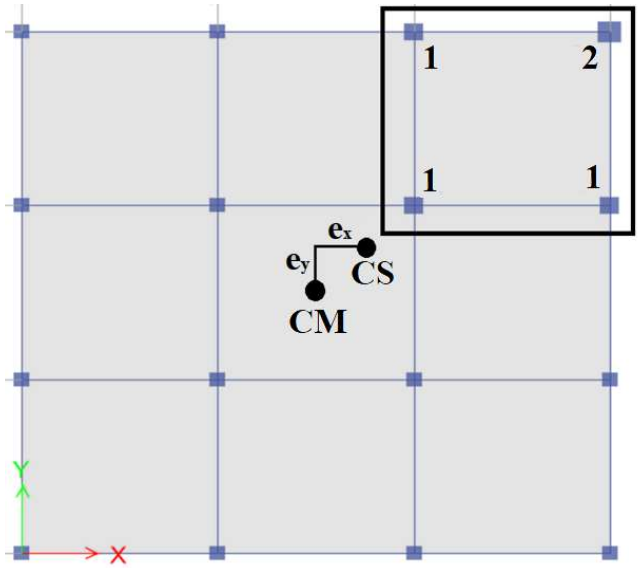

Fig. 9 Plan of G+5 storied RCC Frame Building with Eccentricity

'2' in figure 9 are required to increase for increasing the eccentricity. The dimensions of these columns for various cases are shown in Table 3. The dimension of remaining all columns is 400mm x 400mm.

For G+5 storied RCC building with shear wall, dimensions of shear wall are 2.5m x 0.23m. All remaining properties of shear wall building are same as frame building. Total five models are considered with eccentricity ranges between 0 to 5%, 5 to 10%, 10 to 15%, 15 to 20% and 20 to 25%, which are 0%, 8.33%, 13.33%, 17.33% and 25%. The eccentricity developed by shifting the center of mass which is done by varying live-load in right sided yellow colour slab panel shown in figure 10. For remaining all slab panels, live load is 2 kN/m^2. For model 4 and 5, with increment in eccentricity by varying intensity of live load in one panel, the structure reaches its critical value and further increment in eccentricity leads to collapse of structural members. Therefore, to make sure the structure is safe, structural configuration needs to change. The dimension of columns is increased as shown in Table 4. For remaining all models dimensions of columns is 375mm x 375mm. For model 5, dimension of the beam is 300mm x 550mm. For remaining all models, dimension of beams is 230mm x 460mm.

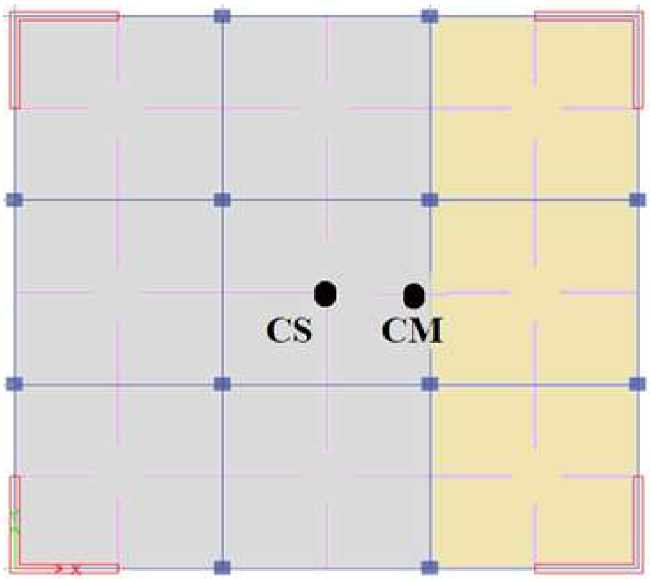

Fig. 10 Plan of G+5 storied RCC Shear Wall Building with Eccentricity

Table 4 Amount of Live Load for various Eccentricity cases

Model	Eccentricity	Live load in yellow panels	Column Size
1	0%	2 kN/m^2	375mm x 375mm
2	8.33%	4 kN/m^2	375mm x 375mm
3	13.33%	6 kN/m^2	375mm x 375mm
4	17.33%	8.5 kN/m^2	400mm x 400mm
5	25%	20 kN/m^2	500mm x 500mm

4. Results and Discussion

4.1 Results of Incremental Dynamic Analysis (IDA)

Incremental dynamic analysis (IDA) has been done by using Seismostruct software using scale factor 0.2 to 3 with increment of 0.2 to evaluate the complete behavior of the structure and to determine fragility curve. Incremental dynamic analysis is also known as dynamic pushover analysis. In IDA constant scale factor multiplies with intensity of ground motion to create monotonically scaled time history. The structure is analyzed under these monotonically scaled time histories, behavior of structure noticed and results are collected. The results of IDA are plotted in terms of Intensity Measure (IM) which are called response cloud. The response clouds of various G+5 storied frame building models and G+5 storied building with shear wall models are shown in figures 11 to 14 and figures 15 to 19 respectively.

From figures 11 to 19 it is noticed that IDA gives the total behavior of structures in terms of required failure criteria at every required acceleration. The trend line in the graph gives linear regression of obtained results from which the pattern of increment in failure of a structure (top drift) to the uncertain parameter (PGA) can identify.

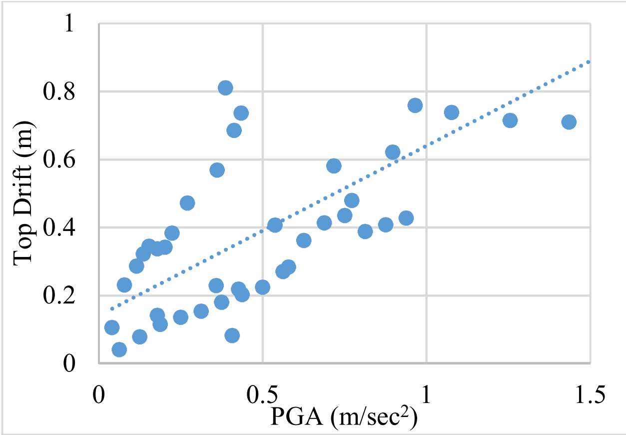

Figure 11 Response Cloud of Frame Building (0% eccentricity case)

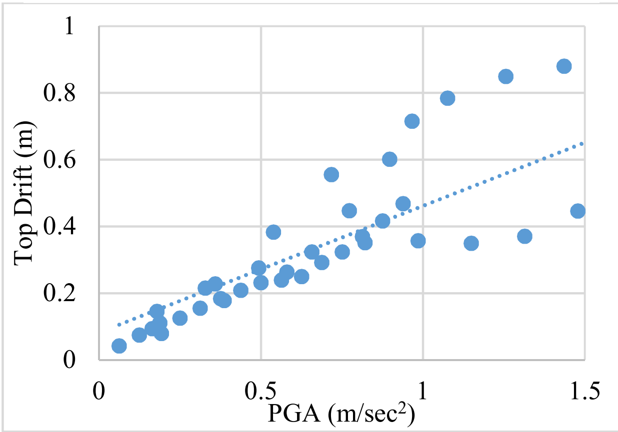

Fig. 12 Response Cloud of Frame Building (7.5% eccentricity case)

4.2 Failure Criteria and Performance Limits

The damage states are considered as per ATC-40 and fragility curve plotted for three failure criteria which are Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP). The static pushover analysis gives failure criteria limits. The results of pushover analysis are represented by pushover curves which is plotted between Displacement Vs Base shear.

Immediate Occupancy means the post-earthquake damage state in which only very limited structural damage has occurred. The basic vertical- and lateral-force-resisting systems of the building retain nearly all of their pre-earthquake characteristics and capacities. The risk of life-threatening injury as a result of structural failure is negligible, and building should be safe for unlimited egress, ingress and occupancy [3].

Life Safety means the post-earthquake damage state in which significant damage to the structure has occurred, but some margin against either partial or total structural collapse remains. The level of damage is lower than that for the Structural Stability Level. Major components have not dislodged or fallen, threatening life safety either within or outside the building. Injuries might occur during the earthquake; however, the overall risk of life-threatening injury as a result of structural damage is expected to be very low. It should be possible to repair the structure [3]. Collapse Prevention means the post-earthquake damage state in which significant damage to the structural elements and total

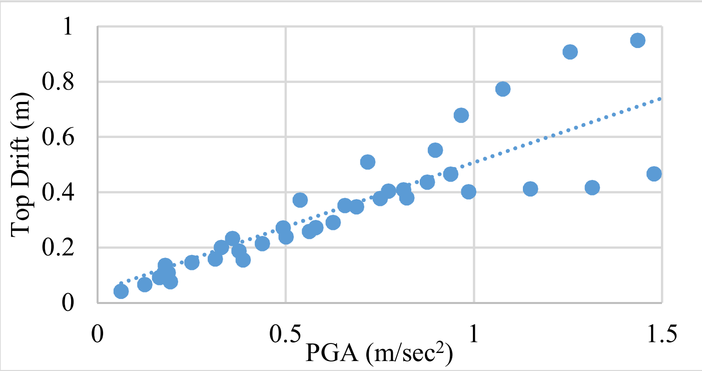

Figure 13 Response Cloud of Frame Building
(13.25% eccentricity case)

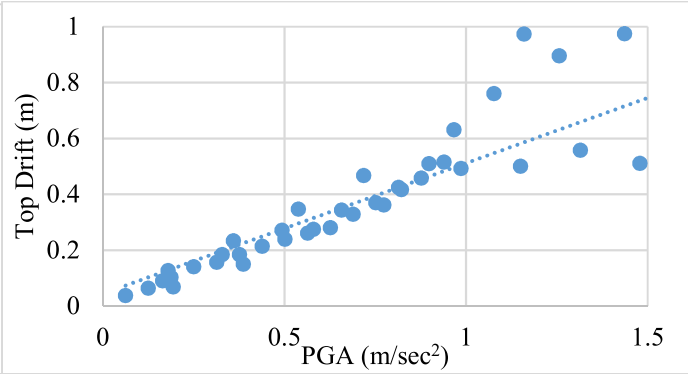

Figure 14 Response Cloud of Frame Building
(17.70% eccentricity case)

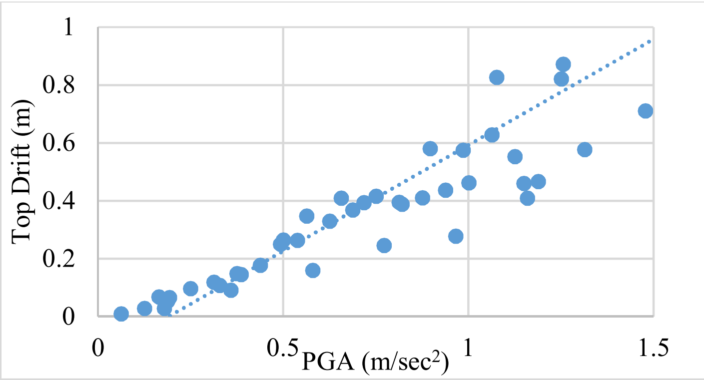

Figure 15 Response Cloud of Shear wall Building
(0% eccentricity case)

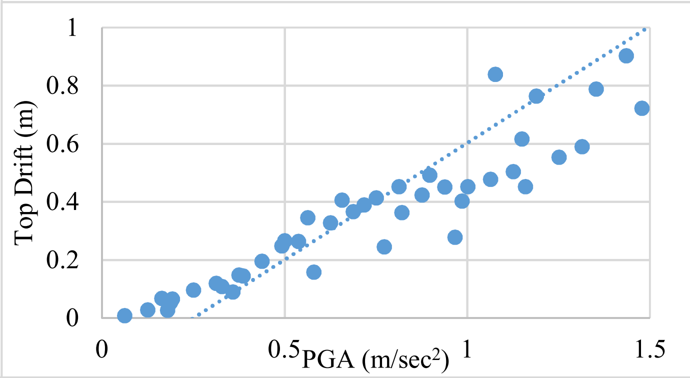

Figure 16 Response Cloud of Shear wall Building
(8.33% eccentricity case)

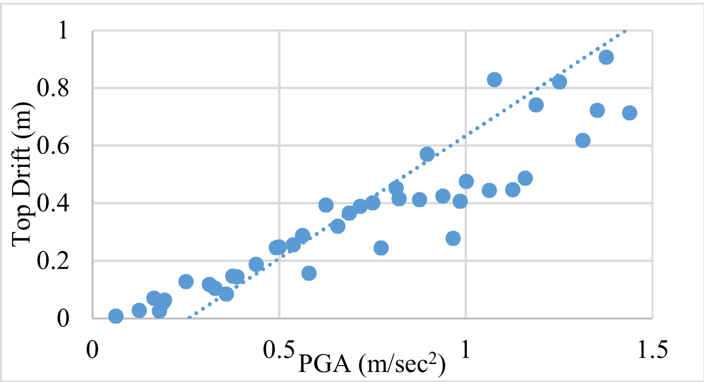

Figure 17 Response Cloud of Shear wall Building
(13.33% eccentricity case)

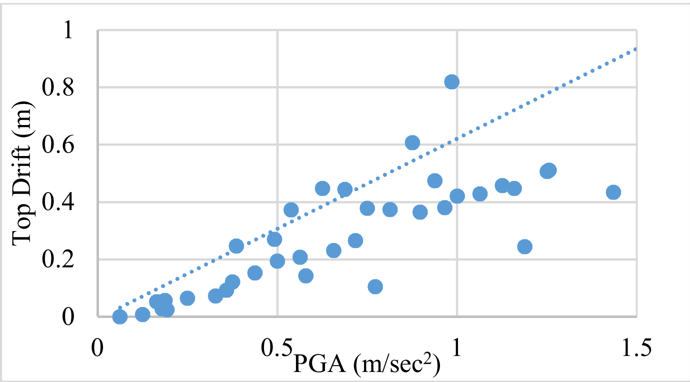

Figure 18 Response Cloud of Shear wall Building
(17.33% eccentricity case)

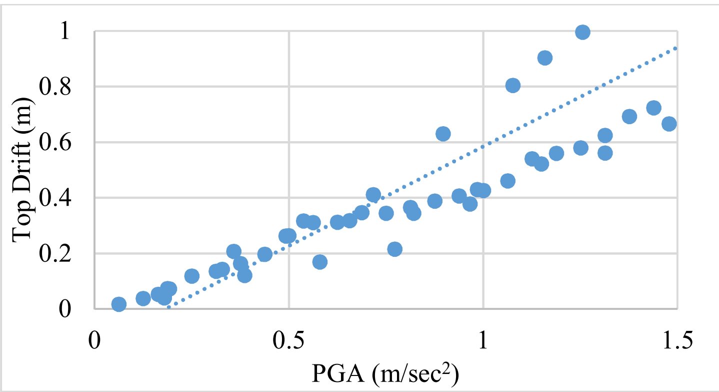

Figure 19 Response Cloud of Shear wall Building
(25% eccentricity case)

collapse of the structure has occurred. The pushover curve of various G+5 storied frame building models and G+5 storied building with shear wall models are shown in figures 20 to 23 and figures 24 to 28 respectively.

From figure 20, it is noticed that the when the load applied to the structure (frame building 0% eccentricity case), its start to deform. For the very first its obey the Hook's low and gives the linear pushover curve. The structure gives non-linear behavior with further application of the load and finally reached ultimate non-linearity limit. Further application of load gives total collapse of the structure. This structure will fail at 1130 kN for Immediate Occupancy failure criteria, at 2017 kN for Life Safety failure criteria and at 2223 kN for Collapse Prevision failure criteria. Similarly, the figures 21 to 28 are also understood.

4.3 Development of Fragility Curve

The fragility curve of G+5 storied RCC frame building and G+5 storied RCC building with shear wall are for various eccentricities are determined by using Monte Carlo method. The Fragility Curve of various G+5 storied frame building models and G+5 storied building with shear wall models are shown in figures 29 to 32 and figures 33 to 37 respectively.

Figure 29 to 37, represent the fragility curves which is plotted between PGA (m/sec^2) as an uncertain parameter to the probability of failure as a considered damage state (top drift). It states that probability of exceeding the top drift from its predefine failure limit. It is noted that increment in PGA increases the probability of failure. As PGA of CP condition is higher as compared to LS & PGA of LS condition is higher as compared to IO, building fails at smaller excitation in LS & even smaller excitation in IO.

5. Comparison of Fragility Curve for Various Eccentricity

5.1 Comparison of Fragility curves for RCC Frame Building

After determination of fragility curve, to know the behavior of structure with constant increasing eccentricity the comparison is required. Therefore, comparison of all cases of RCC frame building is carried out with different failure criteria IO, LS and CP which shown in figures 32 to 34

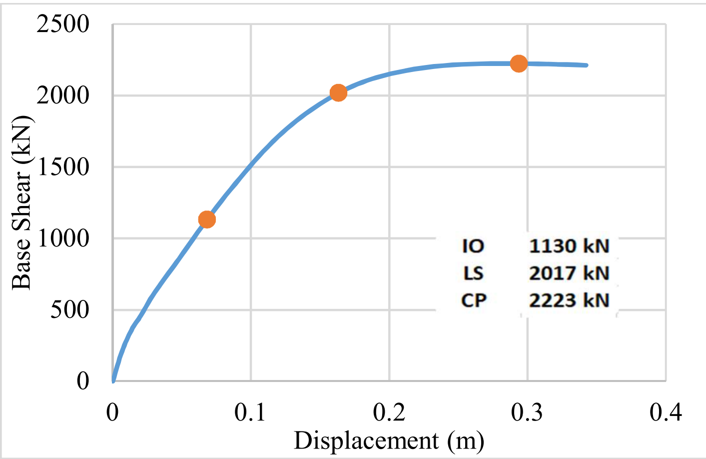

Figure 20 Pushover Curve of Frame Building (0% eccentricity case)

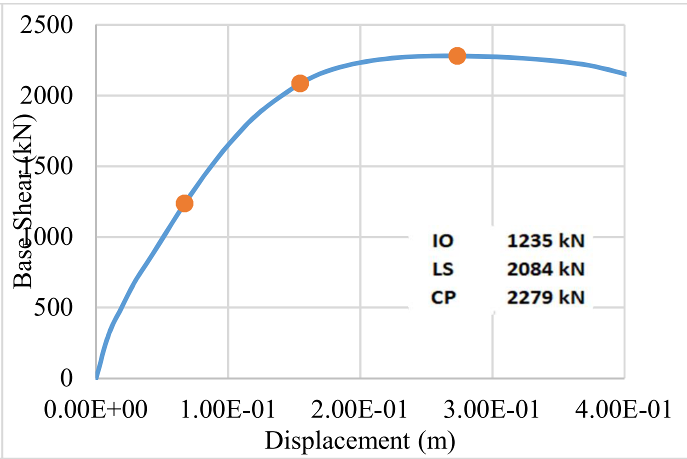

Figure 21 Pushover Curve of Frame Building (7.5% eccentricity case)

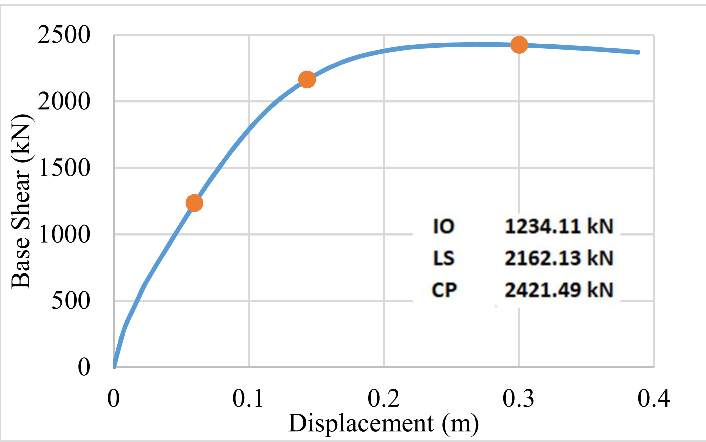

Figure 22 Pushover Curve of Frame Building (13.25% eccentricity case)

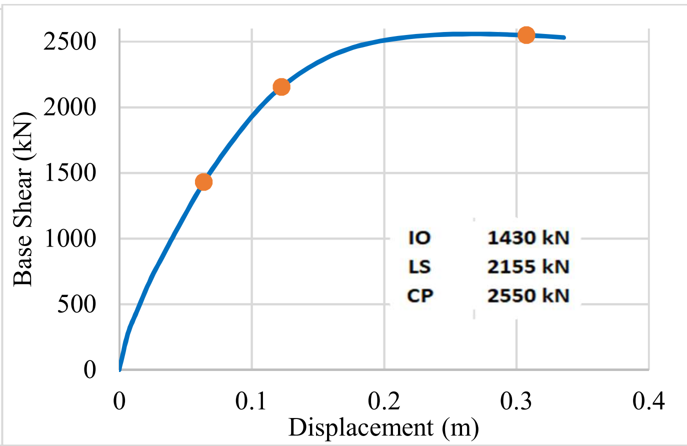

Figure 23 Pushover Curve of Frame Building (17.70% eccentricity case)

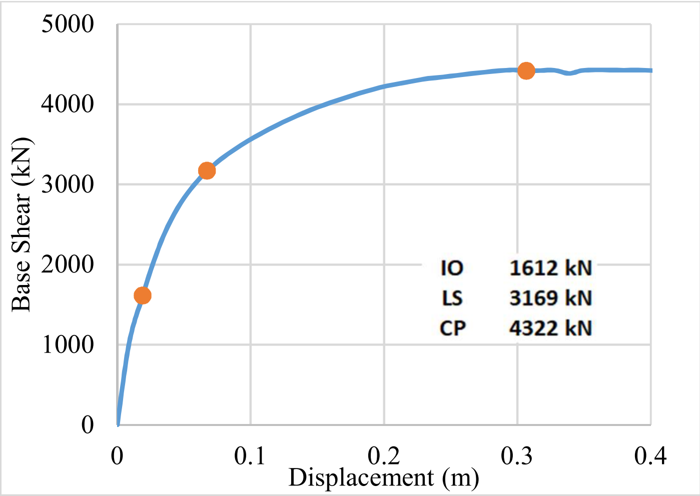

Figure 24 Pushover Curve of Shear wall Building
(0% eccentricity case)

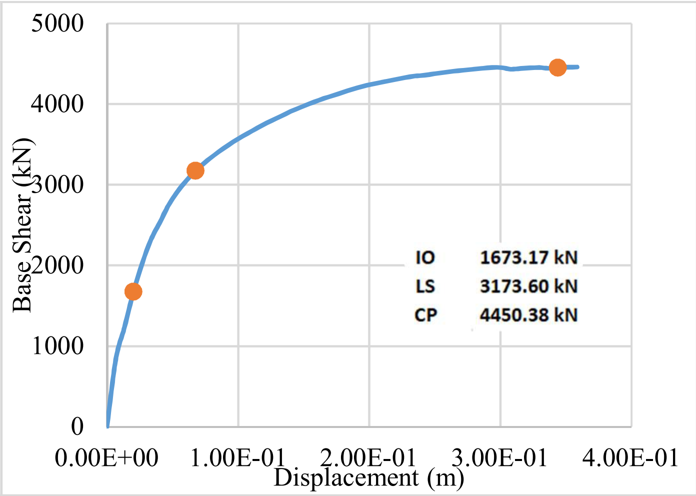

Figure 25 Pushover Curve of Shear wall Building
(8.33% eccentricity case)

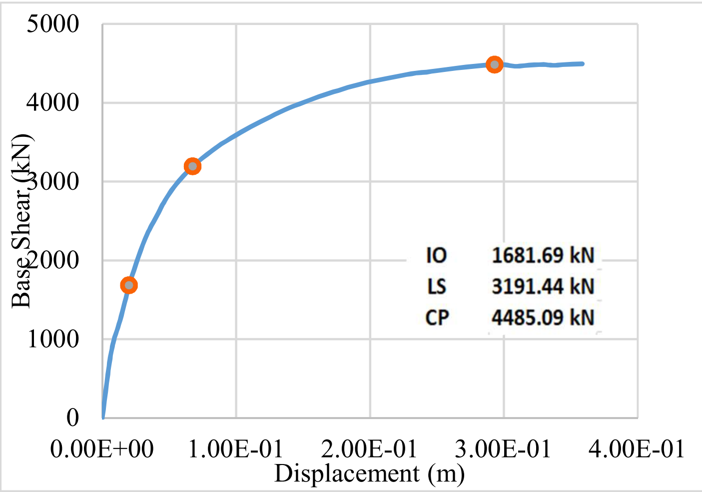

Figure 26 Pushover Curve of Shear wall Building
(13.33% eccentricity case)

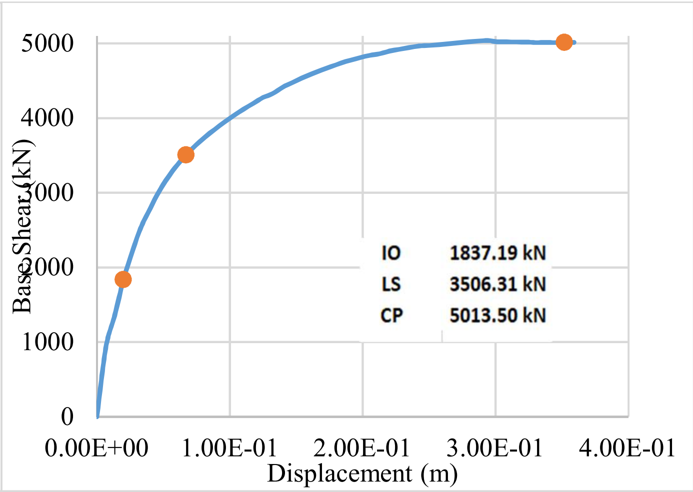

Figure 27 Pushover Curve of Shear wall Building
(17.33% eccentricity case)

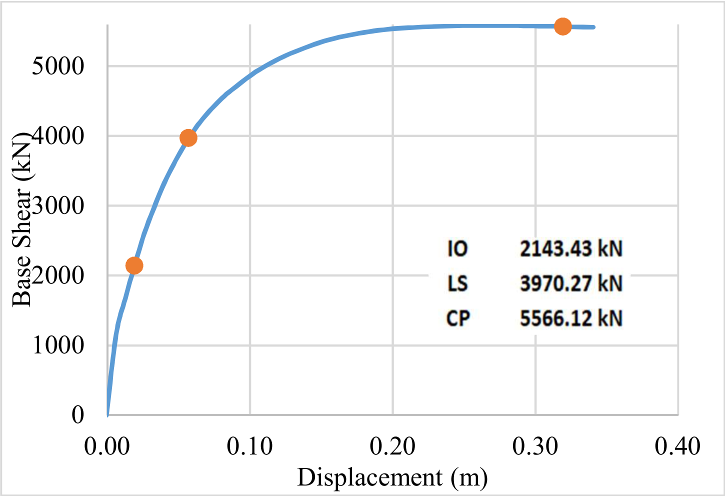

Figure 28 Pushover Curve of Shear wall Building
(25% eccentricity case)

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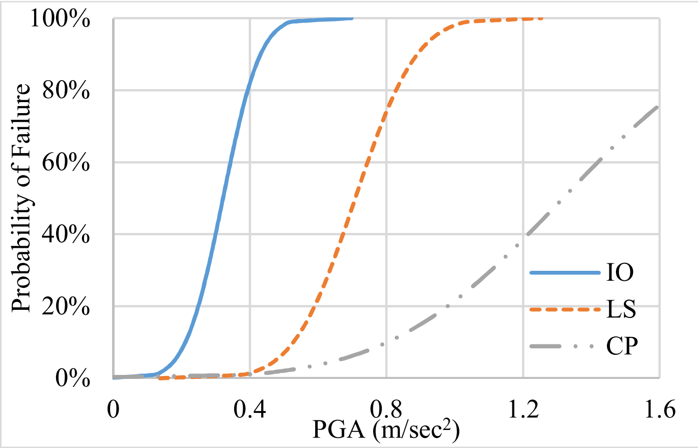

Figure 29 Fragility Curve of Frame Building
(0% eccentricity case)

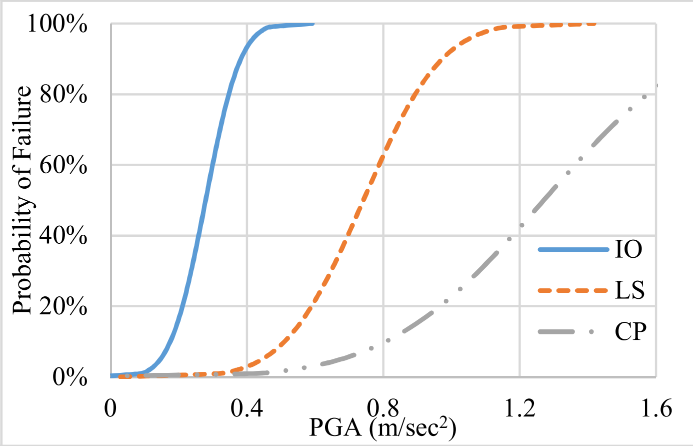

Figure 30 Fragility Curve of Frame Building
(7.5% eccentricity case)

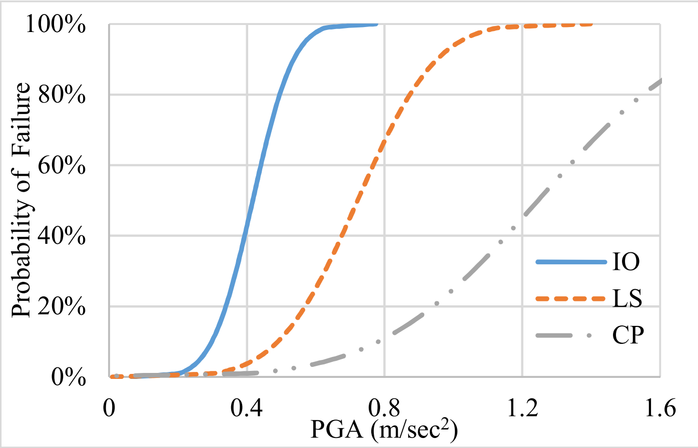

Figure 31 Fragility Curve of Frame Building
(13.25% eccentricity case)

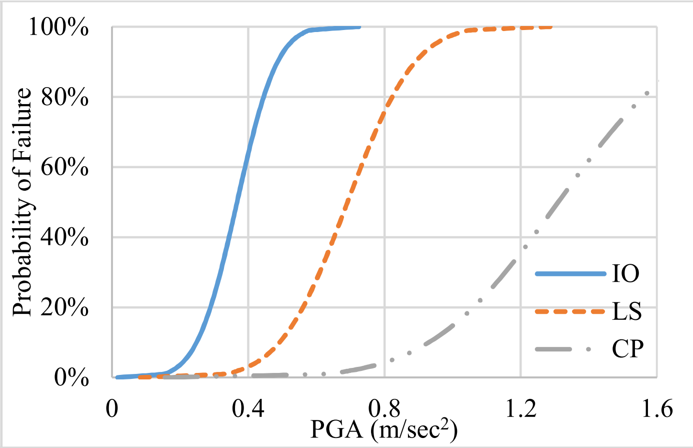

Figure 32 Fragility Curve of Frame Building
(17.70% eccentricity case)

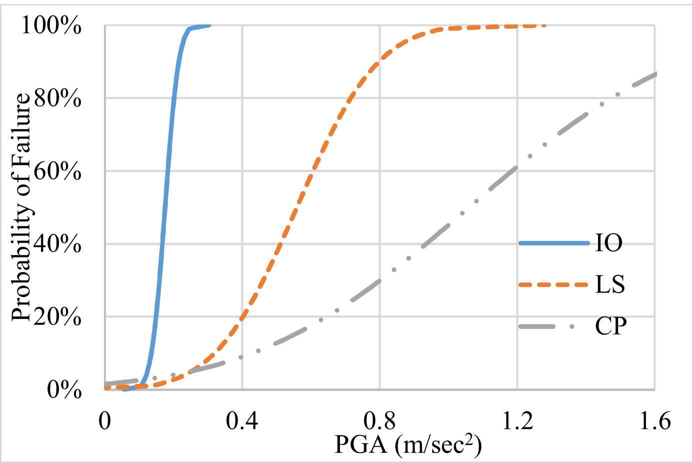

Figure 33 Fragility Curve of Shear wall Building
(0% eccentricity case)

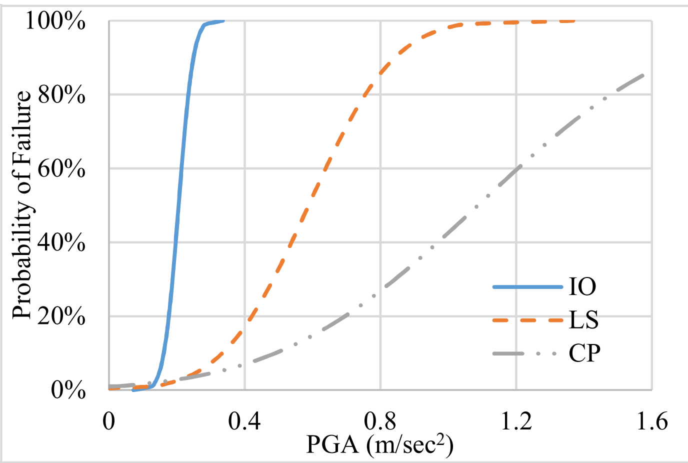

Figure 34 Fragility Curve of Shear wall Building
(8.33% eccentricity case)

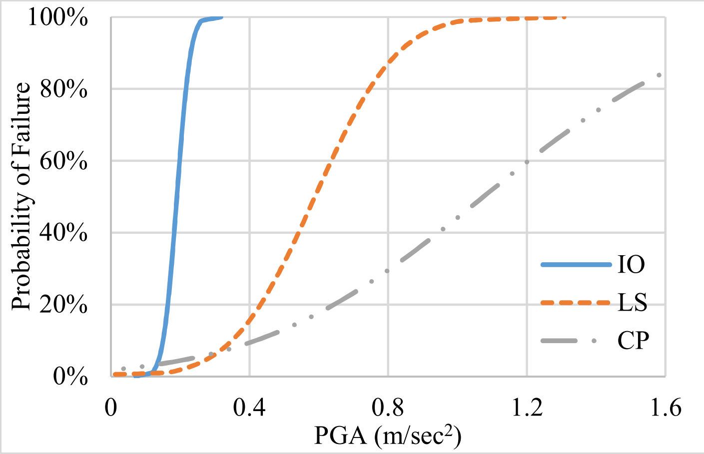

Figure 35 Fragility Curve of Shear wall Building (13.33% eccentricity case)

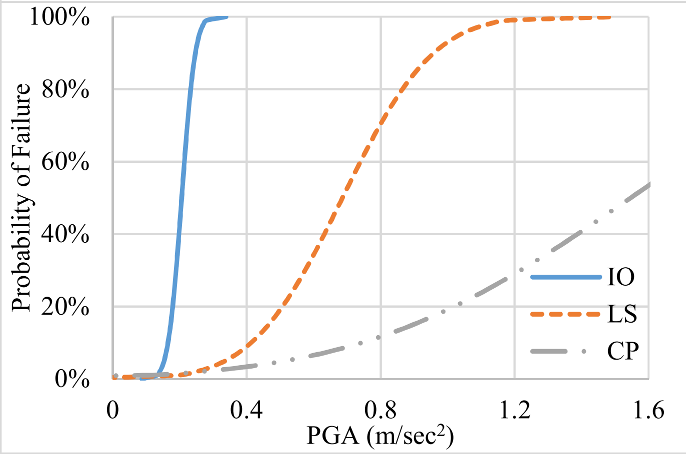

Figure 36 Fragility Curve of Shear wall Building (17.33% eccentricity case)

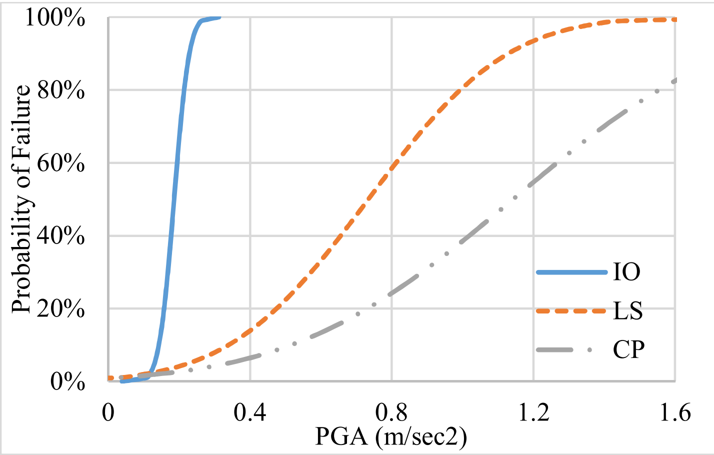

Figure 37 Fragility Curve of Shear wall Building (13.33% eccentricity case)

It is observed from figure 38, for immediate occupancy failure criteria; with the increased in the eccentricity from 0 to 7.5%, the probability of failure increases by 10%; by an increment in the eccentricity from 7.50 to 13.25%, the probability of failure increases to 10%; by an increment in the eccentricity, from 13.25% to 17.70%, the probability of failure increases to 10%. The average increment in the probability of failure is 10% observed.

It is observed from figure 39, for life safety failure criteria; with an increment in the eccentricity, from 0 to 7.5%, the probability of failure increases to 3.00%; by an increment in the eccentricity from 7.50 to 13.25%, the probability of failure increases to 1.64%; by an increment in the eccentricity from 13.25 to 17.70%, the probability of failure increases to 3.26%. The average increment is 2.63% in the probability of failure is observed.

It is observed from figure 40, for collapse prevention failure criteria; with an increment in the eccentricity from 0 to 7.5%, the probability of failure increases to 3.46%; by an increment in the eccentricity from 7.50 to 13.25%, the probability of failure increases to 3.65%; by an increment in the eccentricity from 13.25 to 17.70%, the probability of failure increases to 2.15%. The average increment is 3.08% in the probability of failure is observed.

5.2 The Comparison Fragility Curve for RCC Building with Shear Wall

The comparison of all cases of RCC building with shear wall is carried out with different failure criteria IO, LS and CP which shown in figure 41 to 43.

It is observed from figure 41, for immediate occupancy failure criteria; with increment in the eccentricity, from 0% to 8.33%, the probability of failure increases to 10%; by increment in the eccentricity, from 8.33% to 13.33%, the probability of failure increases to 10%. With increment in eccentricity, the average increment in probability of failure is 10% noticed, when building configuration(i.e. dimensions, grade of concrete & other physical properties) are not changed.

Further, from figure 41, the behavior of fragility curve does not follow the pattern of increasing probability of failure by10% for case 17.33% eccentricity and case 25% eccentricity is explained here. These two cases are becoming critical to further increasing the live load. Therefore, the dimension of columns is increased as shown in Table 4. With the increment in physical properties of the structure, the capacity of structure increases and probability of failure decreases. As plan dimensions for all the cases is not altered, the nature of the fragility curve remains unchanged.

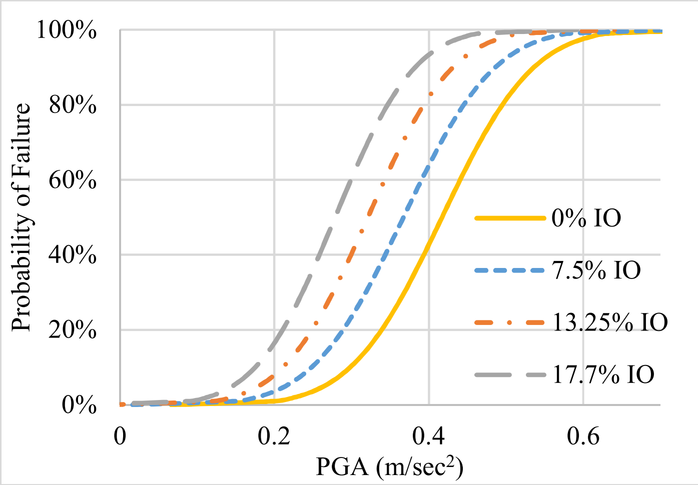

Figure 38 Comparison of fragility curves IO (Frame Building)

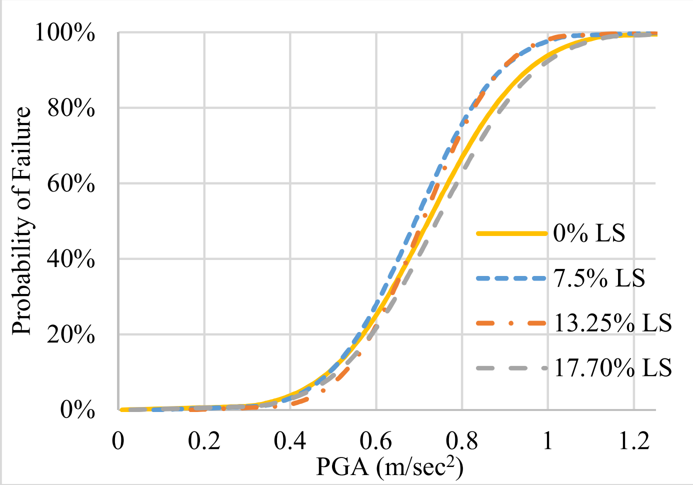

Figure 39 Comparison of fragility curves LS (Frame Building)

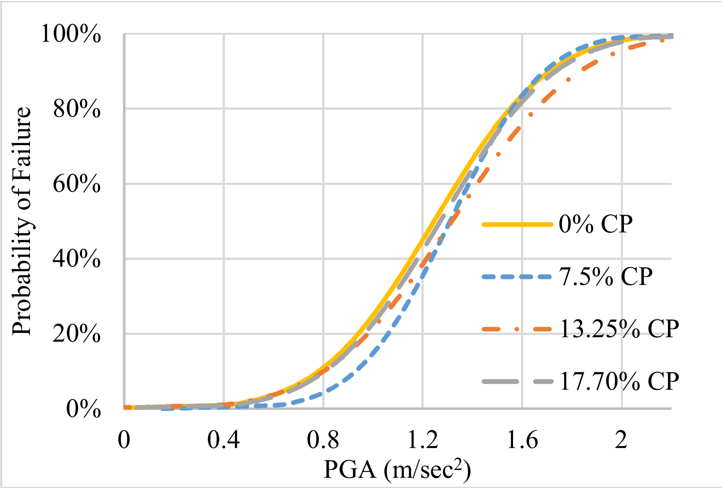

Figure 40 Comparison of fragility curves CP (Frame Building)

Also, the building configuration is changed for eccentricity cases of 17.33% and 25%, the requirement of concrete and steel is shown in figures 44 and 45. From figure 44, it is identified that the requirement of concrete is 4.92% higher in eccentricity case of 17.33% and requirement of concrete is 63.8% higher in eccentricity case of 25% than other cases. From figure 45, the requirement of steel is 8.5% higher in eccentricity case of 17.33% and requirement of steel is 64.3% higher in eccentricity case of 25% than other cases.

From figure 42, for life safety failure criteria; with increment in the eccentricity, from 0% to 8.33%, the probability of failure increases to 0.1%; by increment in the eccentricity, from 8.33% to 13.33%, the probability of failure increases to 2%. The average increment in the probability of failure is 1.1% noticed which is negligible. In the cases of 17.33% eccentricity & 25% eccentricity, with the increment in physical properties of structure, capacity increases and probability of failure decreases.

From figure 43, for collapse prevention failure criteria; with increment in the eccentricity, from 0% to 8.33%, the probability of failure increases to 0.10%; by increment in the eccentricity, from 8.33% to 13.33%, the probability of failure increases to 0.15%. The average increment in the probability of failure is 0.125% noticed, which is negligible. In the cases of 17.33% eccentricity & 25% eccentricity, with the increment in physical properties of structure, capacity increases and probability of failure decreases.

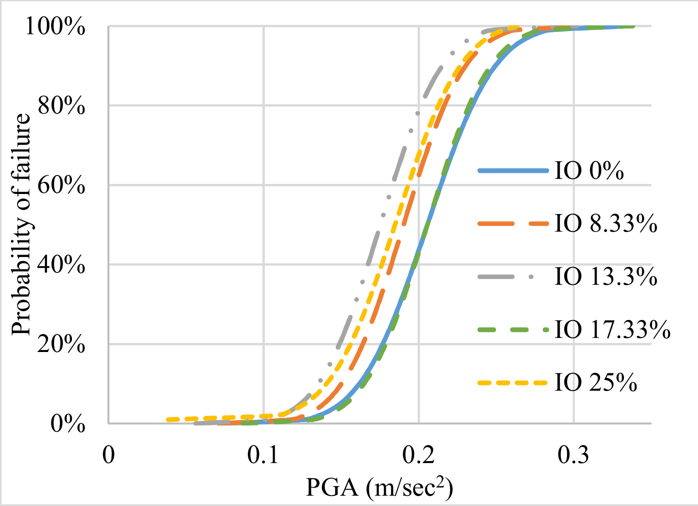

Figure 41 Comparison of fragility curves IO (Shear wall Building)

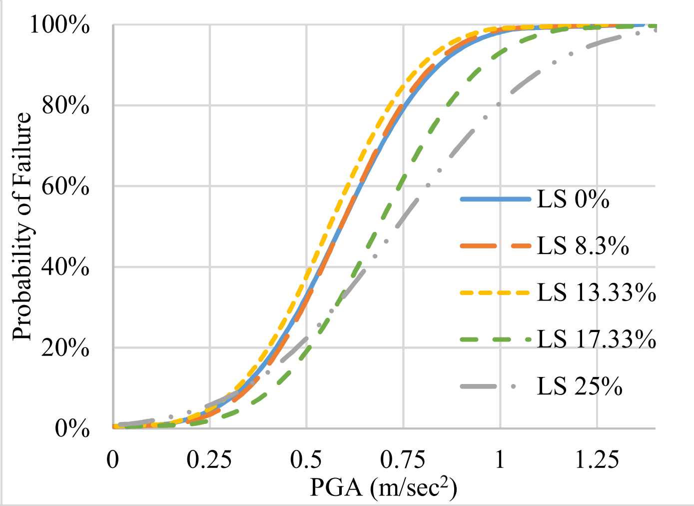

Figure 42 Comparison of fragility curves LS (Shear wall Building)

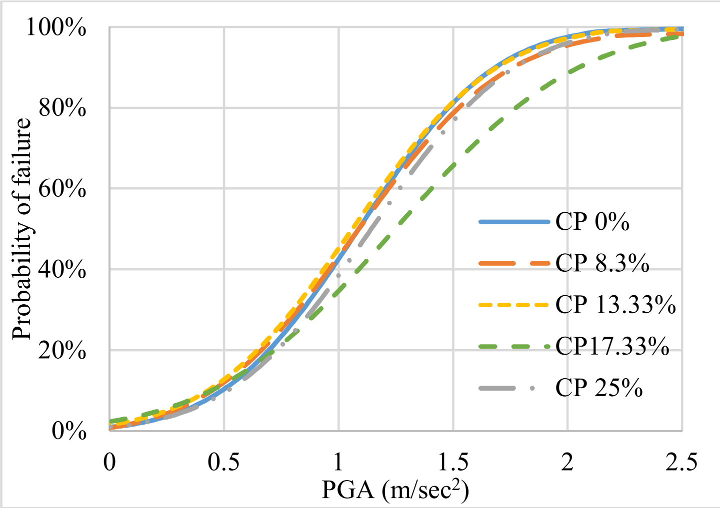

Figure 43 Comparison of fragility curves CP (Shear wall Building)

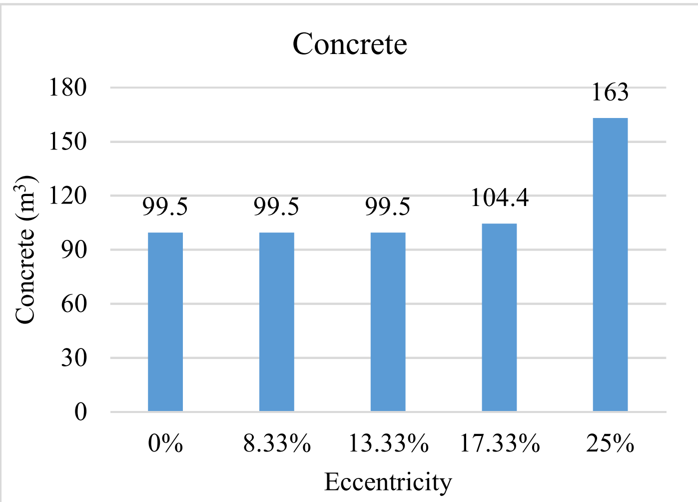

Figure 44 Quantity of Concrete for Shear Wall Building

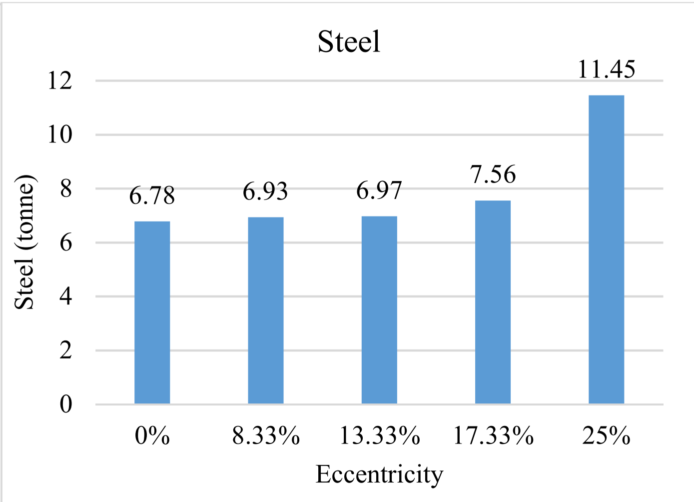

Figure 45 Quantity of Steel for Shear Wall Building

6. Conclusions

In presented paper, asymmetric frame building and G+5 storied RCC building with shear wall with various eccentricity analyzed and design by using Etabs. Performance evaluation and failure limits of various buildings are done by Incremental Dynamic analysis and static pushover analysis by using software Seismostruct. By application of Monte

Carlo method, determined fragility curve for G+5 storied asymmetric frame building and G+5 storied RCC building with shear wall with eccentricity ranges of 0 to 5%, 5 to 10%, 10 to 15%, 15 to 20% & 20% to 25% considering failure criteria in terms of immediate occupancy, life safety and collapse prevention.

From the research work carried out herein, the following conclusions can be drawn.

1. With the increase in peak ground acceleration, the probability of failure increases in all the failure criteria, namely immediate occupancy, life safety and collapse prevention.
2. For the same value of peak ground acceleration, the probability of failure in immediate occupancy criteria is higher than life safety criteria. Similarly, for the same value of peak ground acceleration, the probability of failure in life safety criteria is higher than collapse prevention criteria for asymmetric buildings.
3. The probability of failure is high corresponding to lower values of peak ground acceleration in immediate occupancy criteria. Whereas, for the same probability of failure the peak ground acceleration requirement is higher in collapse prevention criteria as compared to life safety criteria.
4. For immediate occupancy criteria, a significant increment of 10% in the probability of failure is noticed by the increase in eccentricity without changing building configuration.
5. For life safety and collapse prevention criteria, very negligible increment in the probability of failure of about 2 to 5% is noticed by the increase in eccentricity.

Disclosures

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